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Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA

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ABSTRACT

Biochar additions to agricultural soil have been shown to result in numerous potential benefits; however, most studies have been conducted in greenhouse or laboratory trials with few being conducted in the field and particularly in association with organic farming systems. Herein, we address this gap by conducting on-farm studies on the efficacy of locally produced biochar as a soil amendment in small-scale organic agriculture on ten farms in San Juan County, WA. Biochar produced from local timber harvest residues in the San Juan Islands was applied in factorial combination with a poultry litter based fertilizer to replicated plots on all ten farms. Dry beans (*Phaseolus vulgaris* L.) were grown on eight of the farms with green beans and cauliflower being grown on the other two. Soils were examined for nitrogen (N), phosphorus (P), and carbon (C) pools during the growing season. Dry bean samples were evaluated for metal and nutrient uptake. Biochar additions increased soil total C by 32–33%, soil available NH_4^+ by 45–54% through mid-season, pontentially mineralizable N by 48–110%, and citrate extractable P by 29%; biochar additions enhanced soil NO_3^--N, NH_4^+-N, and P retention in the rooting zone by 33%, 53% and 39% respectively. Increased availability of soil P, Fe, Mg, Zn was reflected in the nutrient concentration of harvested dry beans. Our study demonstrates that locally produced wood biochar has the potential to increase soil nutrient availability and uptake. By producing biochar from timber harvest residues and applying them on neighboring organic farms on the San Juan Islands, WA, this study leveraged the local resources and community readiness to drive forest restoration and sustainable agricultural practices in addition to the demonstrated potential short-term benefits of biochar additions for organic farms on the sandy soils of the San Juan Islands.

1. Introduction

Wood biochar has been identified as a potentially effective soil amendment in temperate agricultural systems in North America; however, few studies have directly linked locally produced biochar feedstocks to on-farm applications and fewer studies yet have been conducted on organic farms. In western forest ecosystems fire is a major form of ecosystem disturbance; however, active fire suppression and a shift in forest management objectives has resulted in the occurrence of heavily stocked forests (Naficy et al., 2010; Hessburg et al., 2015) that are subject to stand replacing wildfire. Fuel reduction and forest restoration treatments have been promoted as a means of reducing fire hazard and returning forest stand structure and composition to a more resilient form (Hessburg et al., 2015). Forest residues from timber harvests and fuel reduction treatments are normally piled and burned resulting in generation of air pollutants (CO_2, CO, NO_x and particulate matter), loss of nutrients, and incursion of exotic plant invasion (Kauffman, 1990).

In San Juan County, WA, approximately seventy percent of the land cover is considered to be overstocked second growth forests (San Juan Conservation District, personal communication). Thinning treatments geared toward improving forest health result and reducing fire generate forest harvest residues that require disposal which normally involves pile burning. Pile burning of residues creates air quality problems and is an expense to the land owner. Importantly, a critical part of San Juan County's economy is agriculture and organic farming on well drained sandy loam soils formed in glacial till and outwash. Growing seasons are relatively short and dry due to the "rain shadow" effect created by Olympic Mountains and Vancouver Island. Therefore, biochar production from local timber harvest residues in San Juan County may offer a

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sustainable means of reducing wildfire hazard fuel loading while improving soil health and reducing nutrient loss on neighboring organic farms.

Biochar or charcoal obtained from the thermochemical conversion of forest residues have been studied as a means of creating a low emission, value added product from forest residuals while offering an innovative approach to improving soil fertility and crop productivity (Lehmann and Joseph, 2015). Biochar is a C rich, recalcitrant solid material that is generated from the pyrolysis or thermochemical decomposition of organic material in an oxygen limited environment under controlled conditions.

The application of biochar to soils has been shown to increase soil nutrient retention and microbial biomass, improve N_2 fixation in cover crops, decrease the need for irrigation, and sequester C from the atmosphere (Lehmann and Joseph, 2015). Studies in Midwestern soils, for example, illustrate that biochar decreased N and P leaching by 11% and 69% respectively (Laird et al., 2010). More recently, Ventura et al. (2013) reported a 72% reduction of NO_3^- leaching in sub-alkaline soils in an apple orchard (Ventura et al., 2013). Studies have demonstrated that biochar addition to soils can increase soil microbial biomass, and may also affect the soil biological community composition, which in turn will affect nutrient cycling and plant growth (Zhang et al., 2014). Some biochar studies have illustrated even greater benefits with calcium (Ca) and magnesium (Mg), increasing uptake by between 77 and 320% (Major et al., 2012). Biochar has also been reported to help decrease irrigation demands by increasing soil-water retention (Karhu et al., 2011).

Biochar has been identified as an effective soil C sink as it has high proportion of recalcitrant C with stability measured in hundreds to thousands of years (Lehmann and Joseph, 2015). Its highly porous structure, large surface area may offer appropriate habitat for beneficial microorganisms to flourish; other physico-chemical properties such as high ion-exchange capacity can also impact a number of processes in the soil N cycle associated with enhanced soil fertility (Clough et al., 2013).

The response of soil fertility and plant productivity to soil application of biochar has been highly variable. Fertility responses can vary with the nature of the biochar feedstock, application of an activation or inoculation step, total application rate, crop species, soil type and other soil inputs, as well as combination of these factors (Jeffery et al., 2015). A meta-analysis of biochar effects on crop production by Jeffery et al. (2011) suggests that a biochar application rate lower than 1–5 Mg ha^{-1}, or more than 150 t ha^{-1}, did not simulate significant yield increases (Jeffery et al., 2011), but crops such as rice, wheat, maize and soybean grown in acidic, OM poor soils often showed increases in crop yield and production when growing with biochar additions of 10–100 Mg ha^{-1}.

Enhancement of crop production by biochar addition is generally attributed to the alteration of soil nutrient availability, liming effect, soil hydrological effects, as well as biotic interactions such as enhanced biological N_2 fixation or mycorrhizal fungi colonization (DeLuca et al., 2015b; Jeffery et al., 2015). However, the majority of biochar trials have been conducted as short-term studies in the greenhouse or growth chamber limiting the validity of the findings. Longer-term field trials have often been conducted at agricultural experiment stations using conventional agricultural production approaches. To date, very few studies have been conducted in the field in active organic farming operations and as a part of a holistic closed loop system. Herein, we address this gap by

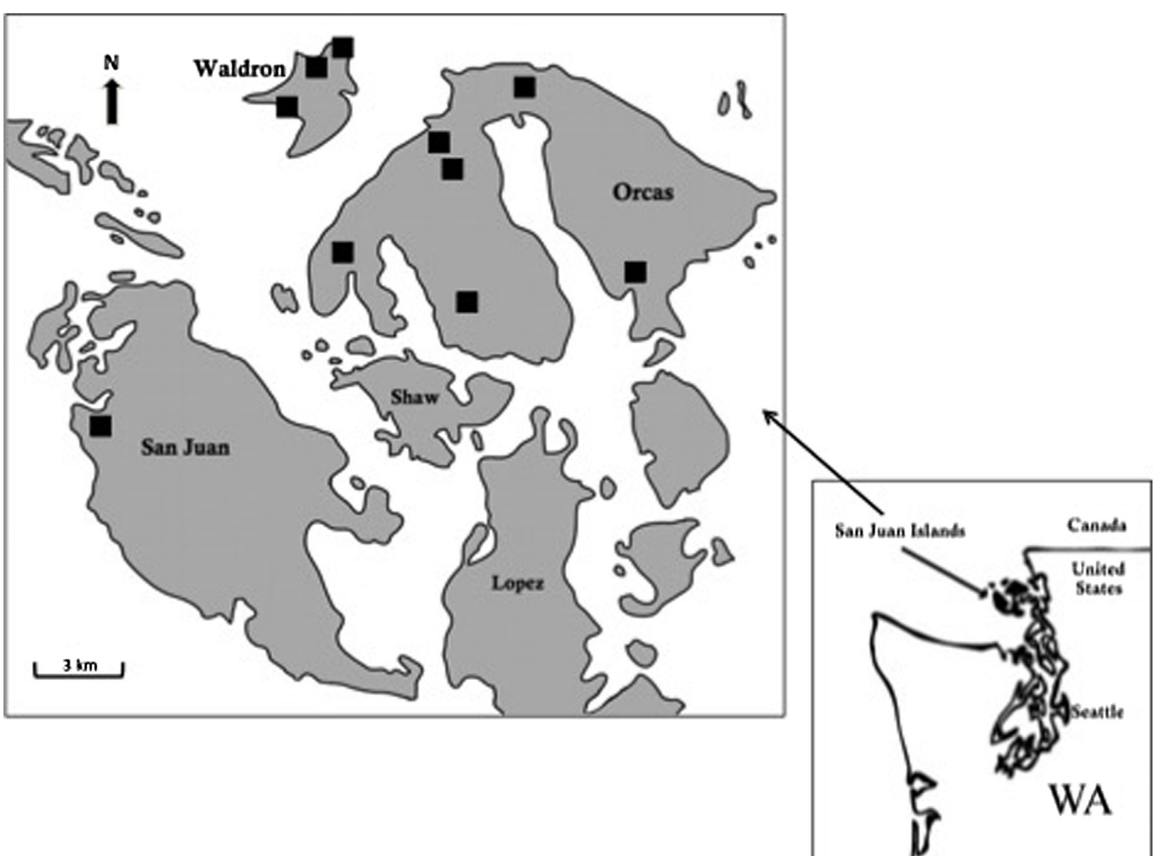

Fig 1. The location of ten organic farms (black squares) in San Juan County, WA, USA.

evaluating the efficacy of locally produced wood biochar as a soil amendment in small-scale organic agriculture. We conducted replicated on-farm trials at ten independent organic farms in San Juan County, WA to examine whether locally produced wood biochar would: (1) increase soil nutrient availability; (2) improve soil nutrient retention; and (3) increase nutrient uptake by dry beans. By producing biochar from on-site logging residues that would otherwise be pile burned with no benefit, we recapture the value of the residues and potentially improve farm soil productivity. Importantly, this is a community cooperative effort that represents operational, on-farm research trials that are of value to the broader research community and regional farming community; as well as leverages the existing resources and community readiness to drive forest restoration and sustainable agricultural practices.

2. Materials and methods

2.1. Study site and experimental design

The study reported herein was performed at ten organic farms located on three islands in San Juan County, WA, USA (Fig. 1). They are Morning Star Farm (48.613 °N, 122.925 °W), Emmet and Brooke Farm (48.629 °N, 123.013 °W), °ceanside Farm (48.622 °N, -122.828 °W), Maple R°ck Farm (48,706 °N, 122.893 °W), CPA Farm (48.623 °N, 122.951 °W) and C°felt Farm (48.673 °N, 122.939 °W) l°cated °n °rcas Island, WA; Sweet Earth Farm (48.561 °N, 123.162 °W) l°cated °n San Juan Island, WA; Huntley Farm (48.718 °N, 123.021 °W), F°rage Farm (48.697 °N, 123.034 °W) and Blue M°n Farm (48.717 °N, 123.011 °W) located on Waldron Island, WA (Fig. 1). A large percent of the San Juan County is covered by forest, consisting mostly of Douglas-fir (*Pseudotsuga menziesii*), Western hemlock (*Tsuga heterophylla*), and Western red cedar (*Thuja plicata*). Most of the remaining land in the county is largely used for agriculture. The climate of the San Juan Islands is influenced by the Olympic Mountains and Vancouver Island, situated southwest and west northwest of the San Juan Islands, respectively, which creates a "rain shadow" effect producing less rainfall and experiencing significantly dryer and brighter weather than the surrounding locations. Summers are relatively short, cool and dry, with an average summer temperature of 15.2 °C; winters are mild and moderately dry when compared to other portions of northern Puget Sound, with an average temperature of 5 °C and an average annual precipitation of 740 mm. The soils of this region are predominately sandy loam soils formed in glacial till and outwash with a naturally high leaching capacity. The farms are found on gently sloping landscapes and dominated by three soil Suborders: Xerepts (Oceanside, Maple Rock, Emmet & Brooke, and Huntley); Xeralfs (CPA, Cofelt, Morning Star, Sweet Earth, and Blue Moon) and Albolls (Forage).

Biochar was produced on-site by "Cylinder Burn", which had been chosen as one of the most efficient biochar production methods tested by a group of farmers and foresters at Rainshadow Consulting and Northwest Natural Resource Group (Fig. S1–S3). Biochar was produced in close proximity to farm sites from logging residues which on average consisted of a mixture of about 80% Douglas fir (*Pseudotsuga menziesii*), 15% White fir (*Abies concolor*), and 5% Western red cedar (*Thuja plicata*). In June of 2015, all trials were to be planted to dry beans (*Phaseolus vulgasris* L.); however, dry beans were ultimately only planted on eight of the ten farms with green beans and cauliflower being grown on the other two. As with all on-farm trials, some experimental control is sacrificed in return for the reality of on-farm production. In this case we kept the two sites with green beans and cauliflower, because it was our intent to primarily follow soil nutrient response to the biochar additions.

Since these farms have been applying manure for decades, in order to reveal the "real" biochar effect, in addition to 'control' and 'biochar' treatment, we created a 'poultry litter' treatment and a 'charged biochar' treatment. Treatments consist of: (1) Control: no additional amendments; (2) Poultry litter: applied at 70 kg N ha^{-1} in the form of litter slurry (102 g "8:4:2 Nutri-Rich chicken litter" in 4 l of pond water per subplot); (3) Biochar: applied at 20 t ha^{-1}; (4) Charged biochar (Litter slurry-amended biochar): 20 t ha^{-1} biochar amended with 102 g "8:4:2 Nutri-Rich chicken litter" (70 kg N ha^{-1}). Pond water was used to add with dry poultry litter to the

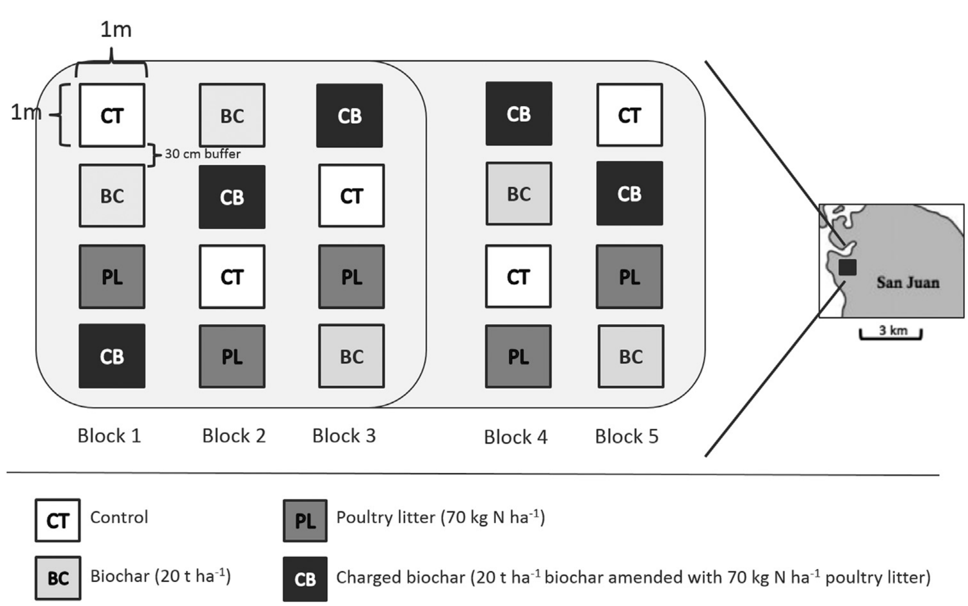

Fig. 2. Example experimental layout with each farm receiving the same four treatments assigned randomly to three or five replicated blocks and each treatment applied to 1 m^2 plots with a 30 cm buffer in between plots at ten organic farms on the San Juan Islands, WA.

biochar, resulting in a moist 'charged biochar'; the same volume of pond water was also applied with the poultry litter, resulting a slurry form of 'poultry litter'. Charged biochar was created by soaking the biochar in the pond water and poultry litter slurry for three days. Three to five replicated blocks were established at each farm site, four treatments were randomly applied within each replicated block, resulting in a total of 136 treatment subplots (Fig. 2). Each treatment was applied to $1 m^2$ ($1 m \times 1 m$) subplot, with a 30 cm buffer in between (Fig. 2). All biochar treatments were incorporated into the top 15 cm of the soil at the beginning of the growing season (May 2015), prior to planting dry beans (Fig. S2). The biochar applied in the study was crushed to create an average particle size of about 2 mm diameter. Replicate soil samples were collected on three separate occasions using a $1 cm^2$ diameter soil core; seven soil subsamples were taken and completely homogenized to create a single composite soil sample per subplot ($1 m \times 1 m$).

2.2. Soil and biochar characterization

Four composite soil samples (0–15 cm) were collected from each farm by taking seven subsamples per composite sample prior to biochar application. The soil was thoroughly homogenized and passed through a 2 mm sieve. Soil pH was determined in a 1:1 soil to water suspension. Total C and N of soil and biochar samples was measured using a CHN analyzer (PE 2400 CHN Analyzer Waltham, Massachusetts USA). Bulk density was measured using a bulk density core that was pressed into the soil. Particle size analysis was conducted by the hydrometer method (Laker and Du Preez, 1982). Water holding capacity was determined by gravimetry (Loveday, 1974). The chemical and physical properties of soil, biochar, and poultry litter are presented in Tables 1 and 2.

2.3. Soil chemical and biological analyses

On two occasions during the growing season soil samples were collected for a suite of chemical analyses. Composite surface soil samples (0–15 cm), composed of seven subsamples, were collected from each treatment subplot at both mid-growing season (June 2015) and at the end of the growing season (September 2015). Soil samples were taken back to the Soil Biogeochemistry Laboratory at the University of Washington and processed within three days of collection. Samples were thoroughly homogenized and passed through a 2 mm sieve. Soil samples (5 g) were weighed out, shaken with 25 ml of 1.0 M KCl, filtered and analyzed for extractable NO_3^-, NH_4^+ using microplate-colorimetric technique using the salicylate-nitroprusside method for NH_4^+ (Mulvaney, 1996) and the vanadium method for NO_3^- (Miranda et al., 2001). Soil potentially mineralizable N (PMN) was measured using 14 d anaerobic incubation method (Bundy and Meisinger, 1996), and was calculated by subtracting initial NH_4^+-N (0 d) from that determined at the end of the incubation (14 d). Soil P status was determined at the end of the growing season using the biologically based P (BBP) method recently described by DeLuca et al. (2015a) that partially capture plant P acquisition strategies. Briefly, soil samples were extracted in parallel with 0.01 M $CaCl_2$, 0.1 M citric acid, phosphatase enzymes, and 1 M HCl and analyzed for orthophosphate using the Malachite green method (DeLuca et al., 2015a). Soil microbial biomass N was determined by using fumigation extraction with amino-N determination by reaction with ninhydrin (Brookes et al., 1985).

Table 2
Total C and N of poultry litter and biochar used in on-farm field trials on the San Juan Islands, WA.

Amendment	Total C (%)	Total N (%)
Poultry litter	40	8
Biochar	69.61	0.112
Charged biochar	68.89	0.469

2.4. Soil accumulation of nutrients below rooting zone

Ionic resin capsules (UNIBEST Ag Manager, mixed anion and cation resin) were installed at approximately 25 cm deep in each treatment subplot at mid-growing season (June 18th 2015). Generally, with the help of a soil core, resin capsules were buried at an angle instead of vertically to protect the rooting system of the dry beans and avoid creation of a preferential flow path. Ideally, nutrients around the resin capsules that were leaching down or lost below the rooting zone could be caught in the resin capsules. Resin capsules acted as a trap, continually exchanging ions for specific counter ions, thus various exchangeable nutrients could be monitored simultaneously. Resin capsules were retrieved at the end of the growing season (September 12th) after remaining in the soil for three months. Resin capsules were extracted sequentially with three 10 ml aliquots of 0.5 M HCl and analyzed for NO_3^--N, NH_4^+-N, and PO_4^{-3} by colorimetry (as described above) and K^{+1}, Ca^{+2}, Mg^{+2}, Na^{+1}, Fe^{+3}, Mn^{+2}, Cu^{+2}, and Zn^{+2} were measured using an inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo Scientific 6300, Waltham, MA) as described elsewhere (Soltanpour, 1991).

2.5. Dry bean nutrient concentrations

Dry bean samples were collected from each treatment subplot, taken back to lab, washed with deionized water, dried in oven and triturated in a domestic food processor resulting in a homogeneous mass. We used ICP-OES to determine the nutrient concentration in dry bean seeds following a dry-ashing and nitric acid procedure (Soltanpour, 1991; Santos et al., 2008).

Table 1
Soil physical and chemical properties at ten organic farms in San Juan County, WA, USA.

Farm name	Replicate plots	Total C ($g kg^{-1}$)	Total N ($g kg^{-1}$)	Sand (%)	Clay (%)	pH	Bulk density ($g cm^{-3}$)	Water holding capacity (%)
Oceanside	3	42.4	3.8	63.89	19.45	5.77	0.48	35.8
Maple Rock	3	36.4	3.9	48.15	21.79	6.20	0.53	33.7
CPA	3	43.4	4.9	49.14	14.73	5.98	0.41	34.2
Cofelt	3	64.5	5.0	70.22	17.04	6.00	0.47	44.6
Morning Star	3	36.1	2.8	44.51	19.13	5.86	0.34	41.7
Emmet & Brooke	3	50.8	3.6	49.17	23.13	5.99	0.32	47.4
Sweet Earth	5	22.7	1.6	74.92	15.07	5.84	0.52	32.3
Huntley	3	25.9	1.5	78.35	13.10	5.72	0.67	30.0
Blue Moon	5	28.6	2.3	76.82	13.98	5.98	0.88	31.3
Forage	3	50.0	2.6	54.08	16.60	5.58	0.64	53.5

Table 3
Soil physicochemical properties (soil pH, water content, water holding capacity), total C and N content, available N, and P in response to biochar, poultry litter, and charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data are presented as mean ± standard error (n = 10). Data were compared among treatments using Tukey-HSD test following ANOVA. Numbers with the same letter are not significantly different at p = 0.05. No letters following the numbers indicate no significant difference (at p = 0.05) among treatments.

Parameters	Physicochemical properties				Soil total C and N			Soil available N (mg N kg^{-1})						Soil available P (mg P kg−1)			
	Soil pH	Water content (%)		WHC (%)	Total C (g kg^{-1})	Total N (g kg^{-1})	C/N	NO_3^--N		NH_4^+-N		PMN		$CaCl_2$ extractable P	Citrate extractable P	Enzyme extractable P	HCl extractable P
Stage		Mid	End					Mid	End	Mid	End	Mid	End	End			
Control	$5.88^a \pm 0.04$	25.37 ± 0.03	30.55 ± 0.03	$38.50^a \pm 2.50$	$40.1^a \pm 3.9$	3.18 ± 0.37	13.3	3.82 ± 1.92	1.65 ± 0.63	$9.79^a \pm 0.89$	$4.84^a \pm 0.66$	$7.16^a \pm 1.08$	$11.62^a \pm 2.79$	10.99 ± 3.34	$105.63^a \pm 31.93$	48.81 ± 16.83	1129.62 ± 199.87
Poultry litter	$5.76^a \pm 0.03$	26.24 ± 0.03	32.86 ± 0.04	$40.20^a \pm 1.78$	$42.3^a \pm 3.5$	2.95 ± 0.33	15.3	4.34 ± 2.34	1.82 ± 0.70	$14.66^b \pm 1.62$	$6.74^b \pm 0.90$	$9.38^{ab} \pm 1.79$	$16.44^b \pm 4.34$	12.64 ± 4.30	$111.03^a \pm 32.70$	51.05 ± 20.22	1192.52 ± 199.23
Biochar	$6.88^b \pm 0.04$	27.42 ± 0.03	32.80 ± 0.04	$47.94^b \pm 4.65$	$52.8^b \pm 5.5$	3.20 ± 0.35	17.2	4.82 ± 2.45	1.32 ± 0.51	$15.10^b \pm 1.64$	$6.05^a \pm 0.86$	$11.37^b \pm 1.79$	$17.23^b \pm 3.80$	10.34 ± 3.63	$135.79^b \pm 40.64$	51.64 ± 19.56	1238.98 ± 206.30
Charged biochar	$6.95^b \pm 0.03$	28.89 ± 0.04	33.62 ± 0.04	$48.33^b \pm 3.02$	$56.4^b \pm 4.9$	3.19 ± 0.34	19.9	3.70 ± 1.53	1.73 ± 0.60	$21.32^c \pm 2.40$	$7.68^b \pm 1.08$	$19.71^c \pm 2.67$	$21.00^c \pm 4.57$	11.37 ± 3.87	$143.63^b \pm 42.31$	60.77 ± 22.23	1300.52 ± 193.90

2.6. Statistical analysis

Each farm can be considered as a stand-alone, randomized complete block study that can be analyzed individually using analysis of variance (ANOVA), with replicated plots (three or five) serving as block (random factor). We also analyzed across all ten farms with each farm serving as a replicate of the whole experiment (farm site as block, a random factor). This paper will only present the analysis across 10 farms as a whole.

For every response variable (e.g. soil total C), measurements made in each treatment subplot (1 m^2) were averaged among three or five replicated plots to generate farm level values, considering the variability between replicated plots is small ($p > 0.05$). Thus, each farm will generate one response value per treatment. When variables were measured at multiple times over the growing season (i.e., soil NH_4^+-N, PMN), farm level averages were made separately for each measurement time (i.e. mid-growing season, end-growing season). All data were subsequently analyzed using a two-way analysis of variance (ANOVA), with farm sites serving as blocks and treatment combination of control, poultry litter, biochar and charged biochar as fixed factors creating a 2 by 2 factorial design. The treatments on individual farm sites were laid out in a randomized within complete block.

Whenever ANOVAs revealed significant effects among treatments, data were subsequently analyzed using post hoc Tukey's HSD tests to identify differences among treatments. In our study, we specifically care about the comparisons for "biochar" to "control" and "charged biochar" to "poultry litter" to reveal biochar effect; and "charged biochar" to "control" to reveal manure use efficiency. All data were analyzed using R (Team, 2013).

3. Results

3.1. Soil response variables

Soil physicochemical properties (soil pH, water content, and water holding capacity), total C and N, available N and P responses

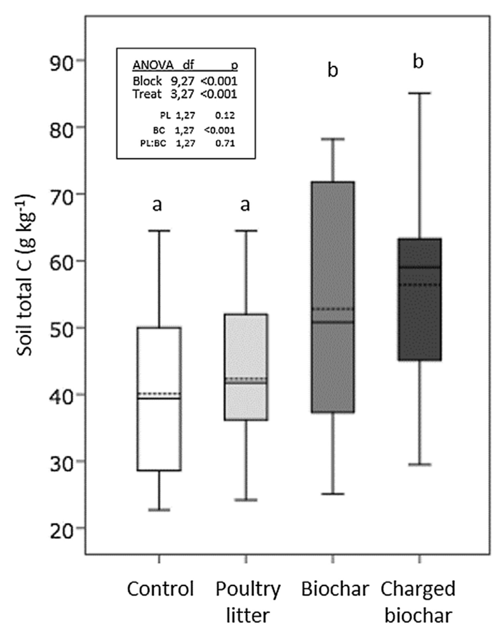

Fig. 3. Total C content (g kg^{-1}) of soils four months after application of biochar, poultry litter, or charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data were compared using Tukey-HSD test following ANOVA. Solid line indicates median, dashed line indicates mean. Columns with the same letter are not significantly different at p = 0.05.

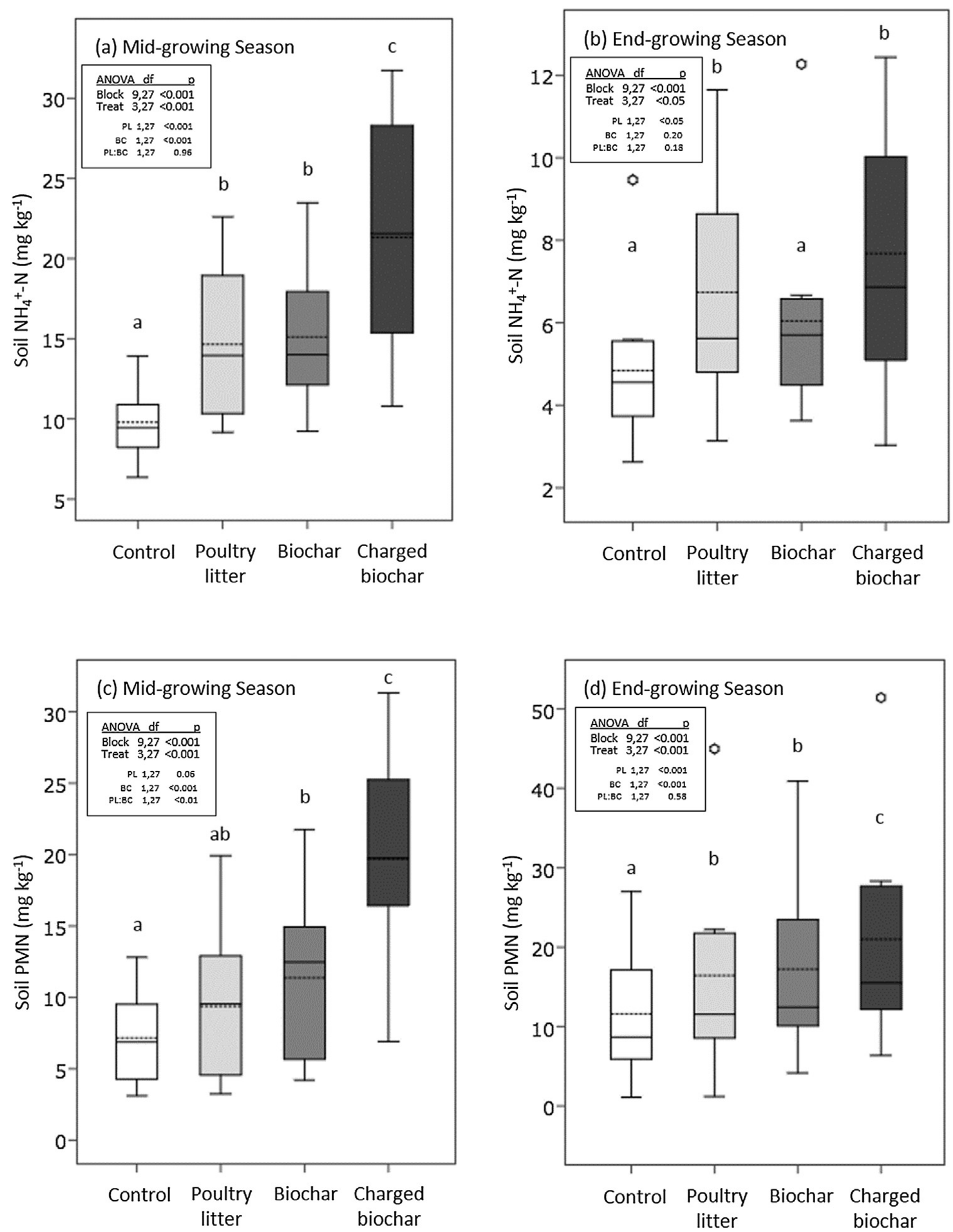

Fig. 4. Soil (a) extractable NH_4^+-N at mid-growing season, (b) extractable NH_4^+-N at end-growing season, (c) potentially mineralizable nitrogen (PMN) at mid-growing season, (d) and PMN four months after application of biochar, poultry litter, or charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data were compared using Tukey-HSD test following ANOVA. Solid line indicates median, dashed line indicates mean. Columns with the same letter are not significantly different at p = 0.05 (all in mg kg^{-1}).

are reported in Table 3, data were presented as mean ± standard error across ten farms when there was no significant block by treatment interaction.

3.1.1. Soil total C

Biochar addition to soil (both 'biochar' and 'charged biochar' treatments) resulted in significantly greater soil total C content (Fig. 3) compared to non-biochar treatments after four months field study. The 'biochar' treatment (52.80 ± 5.48 g C kg^{-1}) increased soil C by 32% compared to 'control' (40.09 ± 3.88 g C kg^{-1}), and 'charged biochar' treatment (56.39 ± 4.86 g C kg^{-1}) increased soil total C by 33% compared to 'poultry litter' treatment (42.33 ± 3.50 g C kg^{-1}).

3.1.2. Soil available N

Soil extractable NO_3^--N, NH_4^+-N, and PMN values were examined at both mid and end of the growing season. Comparing 'biochar' treatment to 'control', and 'charged biochar' to 'poultry litter' respectively allows one to consider the N added with the poultry litter and the N actually contained in biochar itself. In our study, the extractable NH_4^+-N content of biochar is 0.0004 mg g^{-1}, therefore, although the total N content in biochar is reported as 0.112%, a large percent of the total N is recalcitrant N with very little as extractable N (0.0004 mg NH_4^+-N g^{-1} biochar only accounts for 0.008 kg N ha^{-1}; NO_3^- was undetectable in the biochar). Therefore, the NO_3^- and NH_4^+ contributed by biochar itself are considered negligible.

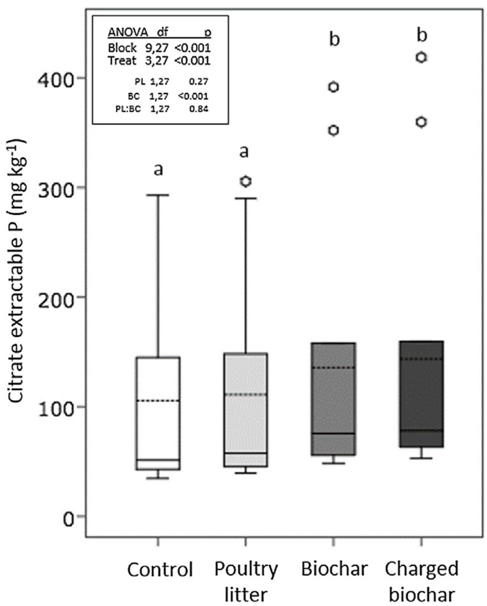

Fig. 5. Soil citrate extractable P concentration ($mg\,kg^{-1}$) four months after application of biochar, poultry litter, or charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data were compared using Tukey-HSD test following ANOVA. Solid line indicates median, dashed line indicates mean. Columns with the same letter are not significantly different at p = 0.05.

Biochar had no significant main effect on soil extractable NO_3^--N contents either during or after the growing season (Table 3). Soil available NH_4^+-N contents increased significantly at mid growth stage in both 'biochar' and 'charged biochar' treatments (Fig. 4a, Table 3). 'Biochar' additions (15.10 ± 1.64 mg N kg^{-1}) increased soil extractable NH_4^+-N by 54% compared to 'control' plots (9.79 ± 0.89 mg N kg^{-1}); 'charged biochar' addition (21.32 ± 2.40 mg N kg^{-1}) increased soil extractable NH_4^+-N by 45% compared to 'poultry litter' treatment (14.66 ± 1.62 kg N ha^{-1}). Although significant differences were also observed between treatments for soil available NH_4^+-N ($p < 0.05$) at end of the growing season, 'biochar' and 'charged biochar' were not significantly different from 'control' and 'poultry litter', respectively (Fig. 4b).

Soil PMN levels (14 d anaerobic incubation) were enhanced by biochar additions as the 'charged biochar' treatment resulted in the highest soil PMN levels at both mid-growing season and end-growing season sampling periods (Fig. 4c, d). At mid-growing season, 'biochar' addition to soil (11.37 ± 1.79 mg N kg^{-1}) increased soil PMN value by 59% compared to 'control' plots (7.16 ± 1.08 mg N kg^{-1}); compared to 'poultry litter' treatment (9.38 ± 1.79 mg N kg^{-1}), 'charged biochar' addition (19.71 ± 2.67 mg N kg^{-1}) improved soil PMN values by 110%. At the end-growing season the 'biochar' treatment had a PMN value of 17.23 ± 3.80 mg N kg^{-1} or 48% higher than the soil PMN values in 'control' plots (11.62 ± 2.79 mg N kg^{-1}). Soils under the 'poultry litter' treatment (16.44 ± 4.34 mg N kg^{-1}) were significantly higher than the 'control', but significantly lower than the PMN associated with the 'charged biochar' treatment (21.00 ± 4.57 mg N kg^{-1}). Overall, biochar significantly increased soil PMN levels in both mid- and end-of-growing season, which represented an active fraction of organic N that could be readily converted into inorganic N for plant up-take.

3.1.3. Soil available P

We evaluated soil P using the BBP method (DeLuca et al., 2015a), wherein four different pools of soil available P are measured in parallel: active inorganic P (citrate extractable P), soluble P ($CaCl_2$ extractable P), organic labile P (enzyme extractable P), and more recalcitrant P (HCl extractable P). Results showed that biochar caused a significant increase (29%) in soil citrate extractable P that corresponds to the active pool of inorganic P sorbed to clay particles or weakly bound in inorganic precipitates which have been shown to be accessible to plants following the release of organic acids into soil (Fig. 5). Soils under 'biochar' and 'charged biochar' additions have a relatively higher citrate extractable P levels (135.79 ± 40.64 mg P kg^{-1}, 143.63 ± 40.31 mg P kg^{-1}, respectively) than the 'control' soil (105.63 ± 31.93 mg P kg^{-1}) and soils under 'poultry litter' treatment (111.03 ± 32.70 mg P kg^{-1}). No significant differences were observed between treatments for soil soluble P ($CaCl_2$ extractable), organic labile P (enzyme extractable), and more recalcitrant inorganic P (HCl extractable) (Table 3).

3.1.4. Soil microbial biomass N

Significant differences between treatments for microbial biomass N were observed and reported in Fig. 6 ($p < 0.001$). Soils in plots treated with 'charged biochar' had higher microbial biomass N than the 'control' treatment. There was; however, no effect on 'biochar' compared to the 'control', or of 'charged biochar' to 'poultry litter'.

3.2. Soil nutrient accumulation below the rooting zone

Accumulated NO_3^--N, NH_4^+-N and P below the rooting zone are reported in Fig. 7, other nutrients are reported in Table 4. Potentially leached NO_3^--N, NH_4^+-N, and P were significantly lower in biochar-treated soils ('biochar' and 'charged biochar') compared to the no-biochar soils ('control' and 'poultry litter') during the three months of the experiment. The 'biochar' addition treatment caused a 33%, 53% and 39% reduction in NO_3^--N, NH_4^+-N and P accumulation in resin capsules at 25 cm depth compared to the 'control' soils, respectively. 'Charged biochar' addition to soils caused a 28%, 50% and 46% reduction of potentially leached NO_3^--

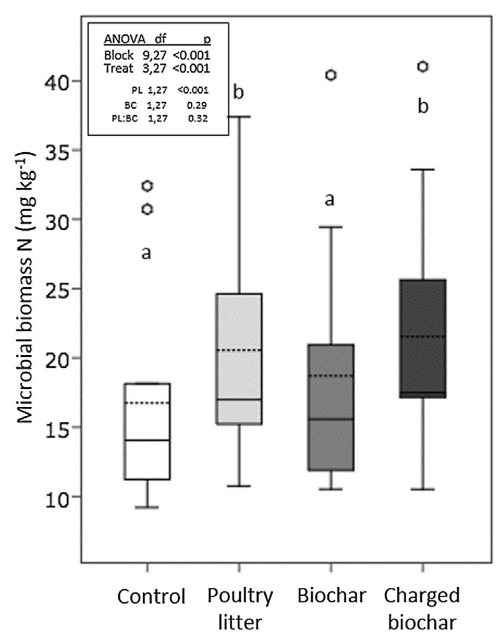

Fig. 6. Soil microbial biomass N concentration ($mg\,kg^{-1}$) measured at the end-growing season after application of biochar, poultry litter, or charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data were compared using Tukey-HSD test following ANOVA. Solid line indicates median, dashed line indicates mean. Columns with the same letter are not significantly different at p = 0.05.

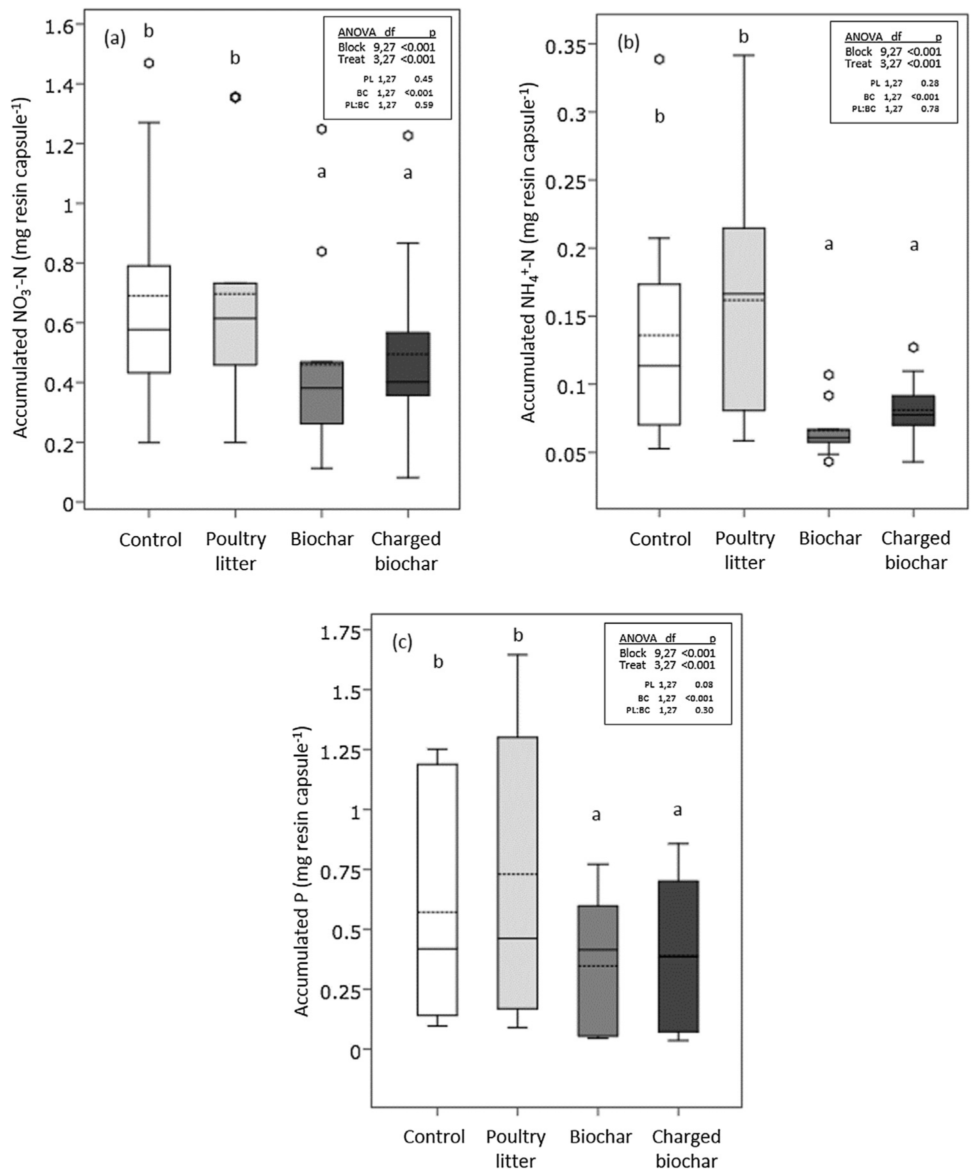

Fig. 7. Accumulated (a) NO_3^- −N (b) NH_4^+-N, and (c) P of resin capsules below the rooting zone during the growing season following after application of biochar, poultry litter, or charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data were compared using Tukey-HSD test following ANOVA. Solid line indicates median, dashed line indicates mean. Columns with the same letter are not significantly different at p = 0.05.

N, NH_4^+-N and P compared to the 'poultry litter' soils, respectively (Fig. 7). It is also observed that biochar caused a retention of Ca, Fe, Mg, Cu, Mn, Ni, Zn after three months (Table 4). Overall, biochar treatments helped reduce the accumulation of nutrients that would otherwise be lost below the rooting zone during this one growing season experiment.

3.3. Dry bean nutrient concentration

The nutrient concentration of 10 elements in dry beans as influenced by biochar and fertilizer treatments is reported in Table 5. The 'biochar' treatment significantly increased P, Fe, Mg and Zn levels in dry beans compared to the 'control'; dry beans in

Table 4
Accumulated nutrients below rooting zone over a three month period[a] in response to biochar, poultry litter, and charged biochar treatments at ten organic farms on the San Juan Islands, WA. Data are presented as mean ± standard error (n = 10). Data were compared among treatments using Tukey-HSD test following ANOVA. Numbers with the same letter are not significantly different at p = 0.05. No letters following the numbers indicate no significant difference (at p = 0.05) among treatments.

Accumulated Nutrients	mg per resin capsule					μg per resin capsule			
	Ca	Fe	K	Na	Mg	Cu	Mn	Ni	Zn
Control	$1.11^b \pm 0.08$	$0.03^b \pm 0.01$	1.06 ± 0.20	1.06 ± 0.22	$0.54^b \pm 0.10$	$0.5^b \pm 0.1$	$8.1^b \pm 1.6$	$0.6^b \pm 0.1$	$5.6^b \pm 0.9$
Poultry litter	$1.18^b \pm 0.03$	$0.02^b \pm 0.00$	1.65 ± 0.42	1.66 ± 0.43	$0.58^b \pm 0.11$	$0.6^b \pm 0.0$	$9.6^b \pm 1.5$	$0.5^b \pm 0.1$	$5.1^b \pm 0.5$
Biochar	$0.70^a \pm 0.09$	$0.02^a \pm 0.00$	1.10 ± 0.15	1.22 ± 0.18	$0.40^a \pm 0.11$	$0.4^{ab} \pm 0.0$	$6.6^a \pm 1.1$	$0.7^a \pm 0.0$	$4.6^a \pm 1.0$
Charged biochar	$0.95^a \pm 0.04$	$0.02^a \pm 0.00$	1.04 ± 0.20	1.28 ± 0.36	$0.42^a \pm 0.01$	$0.4^a \pm 0.0$	$6.7^a \pm 1.1$	$0.3^a \pm 0.0$	$4.6^a \pm 0.9$

[a] 3 month period: from mid-June (mid-growing season sampling) to mid-September (end-growing season sampling).

Table 5
Nutrient concentrations of dry beans under poultry litter, biochar and charged biochar treatments in on-farm field trials on the San Juan Islands, WA. Data are presented as mean ± standard error (n = 10). Data were compared among treatments using Tukey-HSD test following ANOVA. Numbers with the same letter are not significantly different at p = 0.05. No letters following the numbers indicate no significant difference (at p = 0.05) among treatments.

Nutrients ($mg\,kg^{-1}$)	Cu	Fe	Mn	Ni	Zn	Ca	Mg	Na	P	K
Control	17.67 ± 6.75	67.21^{a} ± 7.55	15.28 ± 0.73	1.590 ± 0.34	40.07^{a} ± 5.94	1256 ± 192	1228^{a} ± 25	233 ± 71	3606^{a} ± 344	12415 ± 1047
Poultry litter	20.62 ± 8.24	78.89^{ab} ± 4.96	17.59 ± 1.29	1.340 ± 0.24	39.86^{a} ± 4.77	1244 ± 151	1273^{ab} ± 36	181 ± 33	3979^{ab} ± 285	12676 ± 985
Biochar	25.88 ± 7.86	94.75^{b} ± 9.88	16.66 ± 1.42	2.120 ± 0.29	54.69^{b} ± 8.87	1426 ± 235	1324^{b} ± 39	217 ± 40	4278^{b} ± 303	15718 ± 3445
Charged biochar	36.99 ± 13.38	83.05^{ab} ± 8.47	16.01 ± 1.26	1.560 ± 0.35	54.91^{b} ± 8.68	1364 ± 218	1279^{ab} ± 36	284 ± 78	4349^{b} ± 323	13971 ± 1200

'charged biochar' plots took up significantly more Zn than 'poultry litter' plots or 'control' plots (Table 5), but otherwise there were no significant differences observed between the 'charged biochar' treatment and the 'poultry litter' treatment across the 10 farms.

4. Discussion

4.1. Soil response variables

4.1.1. Soil total carbon

Application of 'biochar' and 'charged biochar' to sandy mineral soils of the San Juan Islands resulted in a significant increase in total soil C (about a 32% increase) compared to no-biochar soils. These findings are consistent with that of numerous biochar studies where researchers evaluate soil C storage (Singh et al., 2012; Fang et al., 2014; Singh and Cowie, 2014; Yang et al., 2016). Since the biochar was applied to surface soils and only incorporated to a shallow depth, the large increase in soil C in the top 10 cm of soil was expected. Given that a large fraction of biochar is in a recalcitrant form, it is unlikely that the applied biochar would decompose or leach to any degree during the study period. Biochar composition can be crudely divided into relatively recalcitrant C, labile or leachable C, and ash (Lehmann et al., 2011). Biochar produced from woody feedstocks usually has low ash content and low labile C content (Ippolito et al., 2015), therefore, recalcitrant C (fixed C) is the dominant component of a high temperature wood biochar C such as that used in this study. A recent study from Yang et al. (2016) reported that soil minerals can interact with biochar in a manner that leads to interfacial reactions that enhance the oxidation resistance ability of biochar particles, improving biochar stability and thus C sequestration (Yang et al., 2016). And results from a recent meta-analysis of biochar stability suggested that mean residence time (MRT) of labile and recalcitrant biochar C pools (3% and 97%, respectively) were estimated to be about 108 ± 196 days and 556 ± 483 years, respectively; with the analyses across 108 observations from 24 studies using stable (^{13}C) and radioactive (^{14}C) C isotopes (Wang et al., 2015). These results as well as numerous other studies cited by (Lehmann and Joseph, 2015) indicated that only a small portion of biochar is available for microbial decomposition and most of the remaining recalcitrant C contributes directly to long-term C sequestration in soil. Generally, high pyrolysis temperatures yield a greater presence of turbostratic C in the biochar (Keiluweit et al., 2010). It has been indicated that the nature of these C structures (fused aromatic C structures) is the main reason for the high stability of biochars (Lehmann et al., 2011).

Compared to conventional farming, organic farming operations tend to have higher levels of soil organic matter that have been built up over time compared to conventional operations with all else equal (Gattinger et al., 2012). Organic farming practices occupy a large portion of agricultural production on the San Juan Islands. Our results confirmed the benefit of on-site produced biochar in increasing soil C storage and illustrated the value-added potential of converting forest harvest residuals to biochar offering an incentive to improve forest management and organic farming.

4.1.2. Soil available N

Most of the N inputs on organic farms on the San Juan Islands come from manure and poultry litter applications that consist primarily of labile organic N which must be mineralized to NH_4^+ or NO_3^- prior to plant uptake (Stevenson, 1999). Our results showed no significant effect of biochar amendments on soil NO_3^--N, indicating that biochar additions did not stimulate nitrification, either during or after the growing season (Table 3). Unlike forest ecosystems where charcoal may enhance nitrification (DeLuca et al., 2006), agricultural ecosystems that receive manure additions and tillage normally have highly active nitrifying communities that do not further respond to charcoal (Ducey et al., 2013; DeLuca et al., 2015b).

Soil NH_4^+-N levels have been proposed as an estimate for soil inorganic N availability in closed-loop organic farming systems (Mikkelsen and Hartz, 2008). Poultry litter (which has a high NH_4^+ content) resulted in a large increase in extractable NH_4^+ in both 'poultry litter' and 'charged-biochar' plots. Interestingly, 'biochar' and 'charged biochar' plots had levels of NH_4^+-N in excess of the control and poultry litter plots respectively during the first sampling (Fig. 4a). This observation is similar to previous studies that demonstrate an increase in NH_4^+ with biochar additions (Dempster et al., 2012; Zheng et al., 2013; Agegnehu et al., 2015). The extractable NH_4^+ content of biochar treatments can only account for 0.19% and 0.83% of the increased NH_4^+-N levels at mid- and end-of-growing season respectively (assuming an average soil bulk density of 0.53 $g\,cm^{-3}$ and a depth of 15 cm, the increased NH_4^+-N concentrations caused by biochar addition scale up to 0.01 mg NH_4^+-N kg^{-1} soil). Therefore, the positive effect of biochar on NH_4^+ availability over the growing season is likely attributed to the adsorption capacity of biochar and the retention of NH_4^+ rather than its N input (Dempster et al., 2012; Pluchon et al., 2014; DeLuca et al., 2015b). Previous studies have shown that biochar retains NH_4^+ in soils through acid functional groups (e.g. carboxyl and hydroxyl) on its surface via cation exchange given biochar's moderately high cation exchange capacity (CEC) (Cheng et al., 2006). The CEC of biochar has been reported to have the potential to increase with residence time in soil, due to its unique surface oxidation with the formation of carboxylic functional groups (Cheng et al., 2006; Dempster et al., 2012). The sandy, well drained nature of the soils on the San Juan Islands increases the likelihood that the biochar additions would have an impact on total CEC and nutrient retention in these soils. It is possible that biochar applied during our field study would act as a "slow release fertilizer" that efficiently releases a steady stream of nutrients after most or all of the pores and negative charges are saturated with nutrients by adsorption process. Charging the biochar with poultry litter slurry prior to field application may have accelerated the cation saturation process thereby increasing the NH_4^+-N concentrations in soils with charged biochar treatments. At the end of the growing season, all differences in NH_4^+ concentrations could be ascribed to poultry litter additions, not biochar amendments demonstrating only a short-term effect of biochar on soil NH_4^+ concentrations.

In addition to NH_4^+-N, PMN is used to roughly estimate the availability of organic N over a growing season (Doran, 1987). In this study, we observed significantly greater PMN concentrations in soils with biochar additions than those without biochar (Fig. 4c, d). It is possible that the biochar in this study adsorbed resident organic N compounds (such as amino acids, small proteins and peptides) that added to the total mineralizable N pool (DeLuca et al., 2015b). It is also possible that biochar additions altered mineralizable N by improving soil moisture retention (Table 3) associated with its high micro pore volume given that N mineralization is most active under appropriate soil moisture conditions (Pluchon et al., 2014; Gundale et al., 2016). It is well accepted that length of time that biochar resides in the soil environment influences the amount of organic matter adsorbed onto the biochar surface (Zackrisson et al., 1996).

Compared to conventional farming, the same amount of N input in the form of manure in organic farming is less readily available for plant uptake as it must be mineralized prior to uptake (Poudel et al., 2002; Kontopoulou et al., 2015). The enhanced N availability by biochar additions observed in our study, particularly PMN levels, illustrated active N turnover following organic N input, as well as greatly improved manure use efficiency in across the ten organic farms on San Juan Islands.

4.1.3. Soil available P

Phosphorus can be a primary limiting nutrient in agricultural systems as P is highly insoluble, binds to soil mineral surfaces or is complexed into organic forms that are not readily available for plant uptake. Accordingly, many plants have P acquisition strategies to cope with restricted P supply (Ryan et al., 2001). Dry beans (*P. vulgaris*), are considered a “P efficient crop” that releases organic acids into the rhizosphere to enhance P acquisition during the growing season (Jones et al., 2003; Khademi et al., 2009). In our study we found that citrate extractable P (which represents a chelation based acquisition strategy), to be higher in soils with biochar additions (Fig. 5). Joseph et al. (2013) and Briones (2011) indicated that hydrophobic or charged biochar could surface adsorb organic molecules involved in chelation of Al^{3+}, Fe^{3+}, and Ca^{2+} ions, as biochar tends to attract polar or non-polar molecules and form organo-biochar or organo-mineral-biochar complexes (Briones, 2011; Joseph et al., 2013). Input of N, P and K to organic farming systems tends to be notably lower (34–51% for P) than in the conventional systems (Mäder et al., 2002). Enhanced soil active inorganic P with biochar addition, especially in the ‘charged biochar’ treatment, clearly demonstrates the benefit of biochar in improving soil P availability across the ten organic farms growing dry beans in our study.

4.1.4. Soil microbial biomass N

Biochar treatments had little influence on soil microbial biomass N (Fig. 6) which is similar to recent findings (Lanza et al., 2016). Poultry litter additions accounted for the only observable increases in microbial biomass N (Fig. 6). Clearly poultry litter additions increased the amount of NH_4^+ and mineralizable N in the test plots (Gunapala and Scow, 1998), but had no net effect on mineralizable N by the end of the growing season. This suggests that biochar has the potential to aid in the retention of nutrients, but not specifically stimulate net microbial growth on the char interior or surface (Quilliam et al., 2013).

4.2. Accumulation of nutrients below the rooting zone

Biochar treatments (‘biochar’ and ‘charged biochar’) appeared to reduce the amount of NO_3^-, NH_4^+ and PO_4^{-3} accumulated on ionic resins below the rooting zone in comparison to the ‘control’ and ‘poultry litter’ treatments (Fig. 7). A reduction in nutrient leaching after biochar application has been reported in laboratory and greenhouse based studies (Laird et al., 2010; Borchard et al., 2012; Dempster et al., 2012; Ippolito et al., 2012; Kameyama et al., 2012; Yao et al., 2012) and in a few field studies (Major et al., 2012; Güereña et al., 2013; Ventura et al., 2013). Soil NH_4^+ leaching has been found to be reduced with biochar additions in many cases (Ding et al., 2010; Laird et al., 2010; Singh et al., 2010) with the primary rationale being the high CEC of biochar given the negative electrochemical charge on the biochar surface (Cheng et al., 2006; Dempster et al., 2012). The observed 30% reduction in NH_4^+ lost below the rooting zone in our study is in agreement with previous findings and further confirmed our observed results of enhanced surface soil NH_4^+-N levels during the mid-growing season. By the end-growing season measurements, it is possible that biochar alone adsorbed soil NH_4^+ thus making it partially unavailable, while ‘charged biochar’ allowed for retention plus the increased N availability associated with the poultry litter used in charging the biochar. This was further confirmed by the reduced accumulation of NO_3^- and NH_4^+ below the rooting zone under ‘charged biochar’ treatment (Fig. 7a, b).

Being a soluble anion, NO_3^- is highly susceptible to leaching in agricultural soils. Our observation of a 30% reduction in NO_3^--N accumulation on resin capsules buried below the rooting zone is consistent with findings from various field studies (Laird et al., 2010; Ventura et al., 2013). Although the specific mechanisms influencing NO_3^- retention by biochar remains unclear, several hypotheses have been proposed:

(1) Microbial immobilization of NO_3^- with biochar additions. The on-farm produced biochar is produced from softwood mix, which is N-limited, but C-rich. It is possible that biochar could increase net NO_3^- immobilization rates thereby reducing NO_3^- leaching (Lehmann et al., 2003).
(2) Biochar increases soil water retention by altering soil physical properties such as enhancing micro- and meso-pores, thereby reducing leaching by reducing water movement through the profile (Glaser et al., 2002; Brockhoff et al., 2010; Ventura et al., 2013). This has particular relevance in this study where soils are sandy and relatively well drained.
(3) Biochar may enhance the growth of soil microorganisms involved in dissimilatory reduction of NO_3^- to NH_4^+, as well as inhibit the activity of *Nitrosomonadaceae* which are responsible for oxidation of NH_4^+ to NO_3^-, thus decreasing the highly mobile NO_3^- pool (Anderson et al., 2011).
(4) Biochar may directly adsorb NO_3^- due to the anion exchange reactions that exist on fresh biochar surfaces (Mukherjee et al., 2011; Zheng et al., 2013) thereby reducing net NO_3^- leaching.

Resin-sorbed PO_4^{-3} is defined as freely exchangeable P that is available for plant uptake. Biochar has been reported to decrease (Novak et al., 2009; Yao et al., 2012; Yuan et al., 2016), increase (Ippolito et al., 2012; Hardie et al., 2015) and have no effect on (Borchard et al., 2012; Iqbal et al., 2015) P leaching in mineral soils. We found a 30% decrease in the accumulation of P in resins below rooting zone, suggesting a potential benefit of biochar in P management in the sandy soils found on the San Juan Islands. Beaton (1959) demonstrated the capacity of charcoal to adsorb phosphate and proposed a mechanism of hydrogen bonding between orthophosphate and charcoal surfaces (Beaton, 1959). However, it is been reported that the amount of P adsorbed to charcoal is relatively low compared to P adsorption on soil surfaces (Nelson et al., 2011). As noted above, dry beans are P-efficient plants (Jones et al., 2003), therefore it is possible that the beans solubilize some amount of P that accumulated at depth. Our study also showed that biochar can help increase the active pool of P that sorbed to soil minerals (Fig. 5), thus partially explained the decrease of resin-sorbed P below the rooting zone.

4.3. Dry bean nutrient concentrations

Dry beans are an important part of the human diet in many countries throughout the world. They supply protein, complex carbohydrates, food fiber, essential vitamins and minerals, are low in fat and contain no cholesterol (Geil and Anderson, 1994). The concentrations of magnesium (Mg), phosphorus (P) and zinc (Zn) in dry beans grown in the 'biochar' treatment were significantly higher than those in the 'control' suggesting that biochar has the potential to help improve nutritional values of dry beans grown on organic farming systems in San Juan Islands. Increased soil available P following organic acid exudation, and decreased accumulation of P below rooting zone were both reflected in the P concentration in dry beans. The decreased resin-sorbed accumulations of metals below the rooting zone (Fe, Mg, Zn) were also reflected in the dry beans (Tables 4 and 5). Charging or inoculating biochar with nutrients is reported to potentially lead to improved mycorrhizal nutrient uptake (Hammer et al., 2015). It is possible that biochar serves as a "slow fertilizer" and "nutrient carrier" that adsorb nutrients into its micro-pores and exchanges nutrients onto its surface given its high CEC. However, it is unclear why the mineral levels of dry beans (with the exception of Zn) growing on 'charged biochar' plots did not show a positive response when compared to those under 'poultry litter' treatment or the 'control' (Fig. 8). The nutrient concentrations of beans grown on the 'charged biochar' plots showed a relatively wide concentration range, implying a great degree of variability across the ten organic farms in terms of different beans species.

5. Conclusion

Soils of San Juan County, WA are dominated by sandy soils of glacial origin, which have a naturally high leaching capacity and limited water holding capacity. The area also has an urgent need for forest health treatments to reduce fire risk on this isolated dry-forest ecosystem. The results from this short-term field study on ten organic farms in the San Juan Islands, WA suggest that biochar produced from local fuel reduction treatments and applied alone or when "charged" with poultry litter has the potential to improve potentially mineralizable N, and P availability, increase nutrient retention, and increase dry bean nutrient concentrations. By producing biochar from local timber harvest residues and applying them in neighboring agricultural soils, our study illustrated an overall positive benefit of an integrated agronomic and a local forest management strategy. Organic farming systems strive to create closed nutrient cycles that have lower immediately available nutrients compared to conventional farming. This study is highly unique in testing the efficacy of biochar additions to soils on small organic farms across the San Juan Islands using on-site produced biochar. Further, this study was conducted as a properly replicated, on-farm research project that was integrated into the normal organic farm operations on each of 10 farms. Our results demonstrate improved nutrient availability for crops while generating net soil C storage from the forest harvest as opposed to simple pile burning of these forest residuals. Although we did not measure net increases in yield, total P and metal uptake was increased in bean tissue. An additional short-coming of this study was the fact that it was conducted over a single growing season. Given the fact that the plots were incorporated into the normal farming operations at each of the 10 farms, it was impossible to maintain the integrity of the plots into future growing seasons with on farm tillage demands and relatively large footprint of the experiment on these small organic farms. Further studies will be conducted at a reduced number of organic farms on the San Juan Islands using larger, semi-permanent plots to assess the long-term effectiveness of on-site produced biochar on overall soil health and productivity.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.08.028.

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